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**An apparatus and a method for optical spectroscopy and for optical sensory  
technology and use of the apparatus**

The invention relates to apparatus and methods for optical spectroscopy and to optical sensors.

Optical spectrometers can be divided into dispersive or diffractive spectrometers and Fourier transform spectrometers.

Dispersive (prism) spectrometers or diffractive (grating) spectrometers break down the incident light beam into its spectral components by the wavelength dependence of an angle of deflection or of an angle of reflection. The different spectral components are thereby spatially separated and the spectral component to be determined can be selected (monochromator). The detection of a spectrum then takes place with the help of moving parts in that the different spectral components are selected and measured in succession.

Monochromators are most common with a Czerny-Turner beam path, i.e. with a rotatable planar grating (diffraction grating in reflection) between an entry slit and an

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exit slit and collimator mirrors or collector mirrors independent of one another. The collimator and collector effect an imaging of the entry slit in the plane of the exit slit. The diffraction grating is located in the Fourier transform plane of this imaging system.

The development of spatially resolving detectors (CCD, diode array) now permits the simultaneous measurement of all spectral components in that a separate element of the detector is provided for each spectral component. Such an arrangement manages without any moving parts and utilizes the available incident light substantially more efficiently.

Fourier transform spectrometers are based on an interferometer in which the difference of the optical path lengths of the partial beams brought to interference can be set with high precision. The spectrum can be determined by Fourier transformation from a measurement of the interference signal via a suitable range of path length differences.

Instruments are normally set up in the manner of a Michelson interferometer or of a Twyman-Green interferometer. The mechanical components for the setting of the optical path lengths by moveable mirrors or tiltable mirror pairs and the required collimator for the generation of planar wavefronts are above all technically demanding here.

A further variant of spectrometers uses static interference patterns generated by light beams which are brought to interference at a specific angle, e.g. Fizeau interferometers. The spectrum can be calculated by counting the interference stripes or via a determination of the spatial frequencies of the interference pattern with the help of a numerical Fourier transformation.

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The fact is disadvantageous for these interferometric spectrometers (both for Michelson / Twyman Green interferometers with variable wavelengths and for static interferometers with spatial interference patterns) that the relative spectral resolution is determined directly by the number of the line pairs (Fizeau stripes) measured in the interference patterns. If  $N$  line pairs are counted for a specific wavelength  $\lambda$ , the spectral resolution lies in the order of magnitude of  $\lambda/N$ .

A more recent variant of Fourier transform spectrometers ("spatial heterodyne spectrometers") uses dispersive or diffractive optical elements (diffraction gratings) in order to change the angle between two collimated partial beams of a static interferometer as a function of the wavelength and so to increase the spectral resolution.

The superposition of planar wavefronts is necessarily required here to obtain Fizeau interferograms (Fizeau stripes) which can be broken down into their spectral components by a numerical Fourier transformation after the measurement.

Such arrangements are furthermore based on the translation invariance of the optical Fourier transformation. The incident light is first collimated by a collimator. The collimated beam (planar wavefronts) is divided (amplitude division) and guided over spectrally dispersive or diffractive elements, e.g. over a diffraction grating. The spectrally dispersive optical element lies in the Fourier plane of the collimator in this process. The partial beams, which are superposed again, are then imaged through a collector and a further Fourier transform lens such that a spatially resolving detector again comes to rest in a Fourier transform plane of the entry aperture.

Such arrangements – like Fourier transform spectrometers or conventional monochromators – are therefore dependent on imaging optical systems of high quality. Relatively large focal lengths of the optical systems are in particular required.

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The possible performance capability of dispersive or diffractive spectrometers depends on specific parameters, in particular on the dimensions of the entry slit or the exit slit, on the focal length and aperture of the imaging elements and on the properties of the dispersive or diffractive element itself. Modern instruments almost reach these physically set limits.

The possible performance capability of Fourier transform spectrometers is correspondingly determined by specific parameters, and here in particular by the range and the increment for the variation of the optical path lengths. The performance capability of Fourier transform spectrometers greatly surpasses the possibility of dispersive or diffractive spectrometers.

Fourier transform spectrometers can also almost reach the physical limits of their performance capability, but the technical effort is very high in many cases. Since Fourier transform spectrometers are based on an interferometer, all optical components, and in particular also the moving parts, must be produced and positioned with a precision of fractions of the wavelengths to be measured.

Spatially heterodyne spectrometers are technically less complex, but likewise need both imaging optical components of high quality and dispersive or diffractive optical components of high quality.

The spectral resolution  $d\lambda$  at a wavelength  $\lambda$  of all named spectrometers is directly related to a corresponding coherence length  $l = \lambda^2/d\lambda$ .

To achieve a specific spectral resolution, the spectrometric arrangement must generate defined differences of the optical path lengths of at least the range  $l$ .

The necessity of a collimation of the incident light is thus common to all named spectrometers. The collimator is an imaging optical element of a specific focal length

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f, e.g. a concave mirror or a lens. The entry aperture of the spectrometer is located at the focal point of the collimator.

The spectrometers now explicitly utilize the special properties of the optical Fourier transformation, in particular the translation invariance of the Fourier transformation, i.e. the transformation of a translation in the focal plane to a change of the direction of propagation in the Fourier plane of the collimator.

Monochromators ("4f system": entry slit – f – collimator – f – diffraction grating – f – collector – f – exit slit) influence the propagation direction of the light in the Fourier plane of the imaging system by means of a diffraction grating and thus generate the desired spectral dispersion without essentially disturbing the imaging of the entry slit onto the exit slit or detector (with  $l$  being defined by the geometry of the grating in the beam path,  $f \gg l$ ). The collimator carries out an optical Fourier transformation, the collector takes over the optical retransformation and thus effects the optical imaging of the entry slit into the plane of the exit slit or of the detector.

Fourier transform spectrometers (2f system) necessarily require the collimator (as a rule with  $f$  substantially larger than  $l$ ) to maintain the interference despite optical paths of different lengths, i.e. to superpose the wavefronts suitably at the detector. The translation invariance of the Fourier transformation is in particular utilized here.

With a Fourier transform spectrometer, the numerical Fourier transformation replaces the optical retransformation used with the monochromator.

Fourier transform spectrometers with dispersive elements, which evaluate a spatial interference pattern (spatially heterodyne spectrometers) explicitly require the collimator in the context of an optical Fourier transformation, on the one hand to avoid a blurring of the interference patterns despite a finitely large entry opening (translation invariance), on the other hand to establish the defined and unambiguous

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relationship between the optical spectrum and corresponding spatial frequencies in the resulting pattern which forms the basis for the numerical retransformation.

These spectrometers moreover require an additional optical imaging system ("6f system": entry slit -  $f$  - collimator -  $f$  - interferometer with diffraction grating -  $f$  - collector -  $f$  - exit diaphragm -  $f$  - imaging element -  $f$  - detector plane).

Since both interferometric arrangements and systems imaging at high resolution have to be realized through high-quality optical systems, with large focal lengths as required, and since a minimum size of the components or of the path lengths is fixedly pre-determined by the aforesaid value  $l$  - in dependence on the respective exact arrangement, the technical effort increases quickly as the demands on the spectral resolution grow. A characterizing parameter here is the so-called spectral aperture broadening which occurs despite collimation.

It is the object of the present invention to provide an apparatus and a method for the realization of spectrometers with high spectral resolution with simultaneously substantially lower demands on the quality of the optical components.

The object is solved in accordance with the invention by an interferometric apparatus in accordance with claim 1 and by the use claims and the method claims.

The coupling of the incoming light via defined spatial modes or via a mono-mode coupling is important for the realization of a cost-effective and spectrally highly resolving spectrometer or sensor in accordance with the invention. The aperture broadening disappears under these circumstances; the interference pattern in particular also remains recognizable without an optical Fourier transformation through a collimator and can be evaluated with the help of the methods shown.

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In combination with dispersive or diffractive optical elements for the wavelength-dependent influencing of the wavefronts, such an optical spectrometer permits very much more compact and more flexible designs than previous approaches using imaging optical elements.

The illustrated measuring process or the illustrated method for the orthogonalization of the measured interference patterns is a requirement for the function of such designs since they cannot be evaluated directly with the help of a numerical Fourier transformation.

Preferable embodiments of the invention result from the dependent claims 2 to 34 following on from the main claim. Uses in accordance with the invention result from claims 35 to 38 and a method in accordance with the invention and preferred method variants result from claims 39 to 48.

The invention comprises an apparatus which combines dispersive or diffractive optical elements with an interferometer with the coupling of individual spatial modes and with a detector which can measure the intensity of the resulting interference pattern at a plurality of spatial positions and a method which permits the spectrum of the incident light or direct measured values, which can be derived from such a spectrum, to be reconstructed from an interference pattern measured in this manner.

The apparatus in accordance with the invention is configured such that the interference patterns of respectively different spectral components of the spectral range to be examined differ strongly from one another. Such an interference pattern associated with a specific spectral component is termed a base pattern in the following. The patterns can be considered in one dimension or in two dimensions. An interference pattern generated by such an apparatus in accordance with the invention is considered as a superposition of a multitude of respectively different base patterns.

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The recording of the interference pattern takes place by the detector by the measurement of the intensities at a large number of discrete spatial positions. An interference pattern is therefore in each case present in the form of a fixed number of (measured) values. Precision and illustratable spatial frequencies follow according to the sampling theorem.

In the method in accordance with the invention, an interference pattern is interpreted as a series of (measured) values and so in the context of linear algebra as a vector or in particular as an element of a discrete space of the corresponding dimension. The base patterns introduced above are initially interpreted as linearly independent base vectors of this discrete space in the context of linear algebra.

The method in accordance with the invention is based on the possibility of determining the respectively required base patterns either by calculation or by measurement for an apparatus in accordance with the invention. In the method in accordance with the invention, the spectrum of the incident light can then be gained by breaking down the interference pattern into these base patterns.

The particular advantages of the apparatus and method for the realization of high-resolution or very compact optical spectrometers result from the optical mono-mode coupling which permits the property of the translation invariance of the optical transformation and thus a collimator to be dispensed with. The apparatus can therefore be realized fully without the use of imaging optical elements. This becomes possible in combination with the described methods which utilize the fact that a numerical retransformation of the interference signal for the sought spectrum measured at the detector can be found at least approximately for almost any sufficiently complicated optical transformations.



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The method can be realized in different variants; we will introduce the following definitions for the discussion:

Let  $s$  be a spectrum, represented by discrete spectral components of a specific intensity, i.e. as a vector with the components  $s_n$   $n:1..N$ .

$s$  comprises a specific spectral range of the optical spectrum; the individual components are spectrally close with relation to the considered spectral resolution.

Let  $i$  be the interference pattern measured at the detector.  $i$  is thus a vector which e.g. represents the individual elements of an array detector represented by the components  $i_m$   $M:1..M$ .

Let  $o$  be the spectrum reconstructed as the measurement result by the method or a vector which directly represents the measured values derived from a spectrum, represented in accordance with  $s$  by components  $o_k$   $k:1..K$ .

In case  $o$  represents a spectrum as a rule with  $K=N$ .

The optical transformation  $T$  can be represented as a matrix by  $T s = i$ . The evaluation is first represented as a retransformation  $R$  by  $R i = o$ .

Under very favorable circumstances (good signal/noise ratio, fixed phase position, "spectrally closely" distributed base patterns), a direct (approximate) calculation of  $R$  could take place as the inverse of  $T$ .  $o$  is then (approximately) equal to  $s$ .

The components (vectors) of the matrix  $T$  can be determined with reference to the relationship  $T e_n = t_n$ , where the  $e_n$  are the unit vectors of the spectral components. The possibility is now particularly interesting of actually generating the spectral components  $e_n$ , for instance, with the help of a monochromatic reference light source

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and to determine the  $t_n$  and thus the matrix  $T$  by experiment (i.e. reference measurement or calibration measurement).

As a rule, a determination of  $R$  by inversion of the (measured) matrix  $T$  is not possible, but the retransformation can take place approximately with known  $t_n$  by a correlation. Different correlation methods are possible; a common method is "cross-correlation" based on the scalar product of the discrete Fourier transformation of the respective sequences or vectors to be compared. Using the discrete Fourier transformation,  $F$ ,  $\phi$  and thus approximately  $s$  can be calculated as  $\phi_n = |F(i)F^{-1}(t_n)|$ .

In case the optical transformation is an exact Fourier transformation, only one component of the expression  $F^{-1}(t_n)$  will be not equal to 0, namely the one which represents the respectively corresponding spatial frequency and thus directly represents a spectral component of the spectrum. The base vectors  $t_n$  are here not only linearly independent, but also orthogonal and moreover form the unit vectors of the spatial frequencies. The calculation of  $\phi$  is therefore reduced for precisely this special case to the Fourier transformation of  $i$ .

However, the following two possibilities are deserving of particular interest:

The properties of the optical transformation can be similar to those of a Fourier transformation or the optical transformation can be completely irregular, i.e. form so-called "speckle patterns" ("granulation").

The first case can be represented by a severely erroneous optical Fourier transformation, for instance produced by an optical arrangement in accordance with the invention without a collimator and with very cost-effective optical elements. The base patterns are thus still linearly independent due to the systematic generation, but only approximately orthogonal.

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The second case can be represented by an optical arrangement in accordance with the invention with an interferometer based on a scratched piece of broken glass (extremely cost-effective). The base vectors can here be assumed to be statistically distributed.

For the first case, the method represents a correction, i.e. the poor quality of the optical transformation can be compensated to a very large extent by an adapted retransformation.

In the second case, the spectrum is determined by a purely statistical correlation of the measured values with the base vectors. In this case, a high number of elements of the detector should be assumed. It is in particular favorable to select  $M$  to be very much larger than  $N$ , for instance by using a two-dimensional detector array. The base patterns are not linearly independent due to their statistical nature. The correlation for large values of  $N$  nevertheless shows good results. Very good results are achieved for very large values of  $M$ , since in this case, i.e. of the statistical distribution of  $N$  base vectors in an  $M$ -dimensional space, the base vectors are at least approximately linearly independent.

In this context, different correlation functions for the method can also be considered, in particular stochastic correlations.

A advanced calculation or refining of the results by deconvolution is particularly advantageous, provided that the selected method can be applied to a set of different transfer functions.

In a use of the arrangement in accordance with the invention as a sensor, it can be advantageous not to look for the spectrum as the result of the calculations, but rather directly for the sought measurand.

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For a chemosensor, the base vectors are then not determined by measurement of spectral components, but by recording spectra of the sought substances. A base vector, and thus a component of the result vector, thus does not represent an individual spectral component, but rather directly the sought measured value, i.e. e.g. the concentration of a specific substance corresponding to an optical absorption spectrum.

The same applies accordingly, for instance, to the measurement of layer thicknesses using the characteristic spectral modulation of light transmitted or reflected by thin films.

This adaptive procedure permits the realization of optical sensors for a plurality of applications. The evaluation of the measurements by correlation with previously recorded base patterns permits the direct determination of the sought values without the detour via an analysis of the optical spectrum.

Provided that the interference patterns, i.e. the base patterns for the spectral components in question, are linearly independent within the framework of the resolution and precision of the measurement, the respective spectral components of the incident light, and thus the spectrum, can be determined by correlation of the respective base patterns with the recorded interference patterns.

Provided that the properties of all components of the apparatus are determined with sufficient precision, the required set of base patterns can be calculated.

The possibility is particularly interesting of measuring a set of base patterns for the respective specific design of the apparatus with the help of a suitable adjustable monochromatic reference light source. Since the base patterns in this case already include all types of optical aberration occurring in the respective apparatus, the

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demands on the optical quality of the components of the apparatus are relatively low, provided that the base patterns remain approximately linearly independent.

With Fourier transform spectrometers, the recorded "perfect" interference patterns are linearly independent (superposition of sinusoidal components) and the Fourier transformation represents an orthogonalization method. The individual Fourier coefficients represent the spectral components of the measured spectrum.

A direct Fourier transformation of the patterns recorded with an arrangement in accordance with the invention is meaningless, but an orthogonalization with respect to spectral components is possible after a suitable transformation of the recorded interference patterns. For this purpose, the relative path length difference of the partial beams brought to interference must be determined for each measuring point.

In accordance with a preferred aspect of the invention, the interference pattern can be generated by dividing the amplitude of the incident light with the help of a semi-transmitting mirror or of a suitable grating (optionally into more than two partial beams) and a subsequent superposition of the partial fields at the location of the detector. All classical interferometers can be considered here which are optionally supplemented by dispersive or diffractive elements, for example: Michelson interferometers, Mach-Zehnder interferometers, Sagnac interferometers, Fabry-Perot interferometers or shearing interferometers. Any arrangement, which generates interference patterns with spatial periods, which the respective detector can resolve can furthermore be considered. The spatial frequencies occurring at the detector can be selected independently of the wavelength range to be examined in each case by a suitable dimensioning of the apparatus.

The generation of the partial fields by splitting the wavefront, for instance by a Fresnel biprism, by other combinations of prisms or mirrors, with the help of surfaces of irregular shape or likewise with the help of diffractive elements, can furthermore

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be considered – particularly favorably by the restriction to individual spatial modes of the light field.

The required spectral dispersion can be introduced in all cases by a suitable design of the beam splitter itself or by additional optical elements.

The detector – provided with a suitably small diaphragm – can be moved through the interference pattern (scanning). It is also possible to record the different measurement points successively by moving other components of the apparatus or with the help of an additional movable mirror. This method in particular suggests itself for extremely high-resolution measurements or in wavelength ranges for which no suitable spatially resolving detectors are available.

In the one-dimensional case, a suitable diode array or a CCD line suggest themselves as a spatially resolving detector.

The use of two-dimensional detectors (CCD or other detectors) is particularly interesting, since in this case a substantially broader range for the properties of the base functions exists on the increase of the number of measured values and the respective correlations can be calculated correspondingly more exactly with "better" linearly independent functions.

The Figures show preferred aspects of the invention in respectively different combinations of the different claims.

Figure 1 shows an extremely compact arrangement in accordance with claim 1, with the optical components being integrated in a monolithic glass block. The light coupling (M) takes place in accordance with claim 6 directly from a mono-mode glass fiber into the block so that the field initially develops as a spherical wave. The amplitude of the wave in accordance with claim 2 is split by a diffraction structure (G)

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applied directly onto the glass block into a diffracted component and a reflected component which run to a respective one of the mirrors (S1, S2) applied directly to the glass block. The diffraction structure acts in this process, in accordance with claim 27, both as a beam splitter and as a spectrally highly dispersive optical element which changes the wavefront of the diffracted beam in a spectrally dependent manner. In the further steps, the partial fields are reflected and superimposed again. The illustrated arrangement here functions in accordance with claims 28 to 30. The resulting field exits the glass block via the free surface. A second field consisting of non-used diffracted portions is substantially incident to that surface of the glass body via which the coupling of the spherical wave took place. This portion should be absorbed by a suitable coating of this surface.

The detector (D) has a small spatial extent or has a suitable diaphragm and is located, in accordance with claim 7, on a movable arm, shown with a center of motion (P). The detector is moved through the light field and records its intensity at a plurality of spatial positions sequentially. In the arrangement shown, the movement of the arm is driven with the help of an eccentric device (X), which is driven by a motor (R).

A set of such measurements, i.e. a set of measured values recorded at defined positions, forms a pattern which can be evaluated with the help of the methods in accordance with claims 39-48.

An arrangement in accordance with Figure 2 using a separate beam splitter (S) for the division of the amplitude of the waves in accordance with claim 2 and two dispersive elements (G1, G2) in the arms of the interferometer becomes possible by a mono-mode coupling (M) in accordance with claim 4. An aperture diaphragm (A) as shown is advantageous. Such an arrangement manages without a Fourier transform optical system or fully without any imaging optical elements, since the translation invariance of the Fourier transformation can be omitted. The evaluation of

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the interference patterns, which are generated by such an arrangement, can thus also not take place directly by a numerical Fourier transformation, but requires one of the methods shown in claims 39 to 48. The arrangement shown in Figure 2 uses a spatially resolving detector (CCD) in accordance with claim 9. A phase modulator (P) in accordance with claim 14, for instance in the form of the piezo-actuator symbolized in the Figure, has a particularly advantageous effect.

The possibility of recording interference patterns at a plurality of different relative phase positions of the fields involved provides substantial advantages for the methods shown.

In this case, the set of the intensities respectively recorded by the spatially resolving detector forms a pattern which can be evaluated with the help of the methods in accordance with claims 39-48.

In addition to the advantages of arrangements in accordance with claim 1, which arise from the possible full dispensing with imaging optical elements, permits a mono-mode coupling, in particular also an interferometric arrangement, which are based on a splitting of the wavefront in accordance with claim 3. Beyond the omission of imaging optical elements, this also permits the omission of a beam splitter as a discrete optical element.

Figure 3 shows an arrangement in accordance with claims 1 and 3. The requirement is a coupling (M), for instance in accordance with claim 4. The coupled light field propagates as a spherical wave starting from M. In the arrangement shown, the mirror (S) has a suitable opening through which the coupled field can pass. A portion of the wave is incident to a diffraction grating (G1), another portion is incident to a diffraction grating (G2); the wavefront is thus split. An aperture diaphragm (A) as shown is advantageous. The gratings diffract the light with the highest possible



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efficiency back to the moving mirror (S), where a superimposition of the wave fields takes place.

The moving mirror in accordance with claim 8 reflects the resulting field to the detector (D), which can record the intensity of the field at a plurality of different positions in dependence on the position of the mirror.

It is favorable, but not absolutely necessary, to provide a phase modulator in accordance with claim 14, for instance in the form of the piezo-actuator (P) shown.

An alternative possibility in accordance with claim 15 for the generation of different interference patterns, which can be utilized in the methods shown can be realized in such an arrangement simply by a spatial displacement of the coupling device.

In this case, the pattern to be evaluated by a method in accordance with one of claims 39 to 48 is provided by a set of measured values which were measured for different positions of the mirror S.

The performance capability of the apparatus and of the methods described in the following can be substantially improved if the relative phase position of the partial beams can be suitably influenced. This can take place, for instance, by the use of a mirror which is linearly displaceable over a path in the order of magnitude of the wavelength and by which the relative phase position of the reflected light can be changed with high precision or, e.g. in the case of a design in the manner of a shearing interferometer or, e.g. in the case of a grating with a plurality of spatial frequency components as beam splitters, by a suitable "lateral" displacement of the components.

The interferometric apparatus shown can furthermore be made or further developed such that the differences in the optical path lengths, at which the partial beams are

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brought to interference, differ by a measure introduced by the dispersive element(s). The interferences are then limited to components of the incident light with a correspondingly high coherence length or a small bandwidth.

An interference signal is only generated when the incident radiation shows coherence properties or autocorrelation properties in the range of the optical path length differences. On a use in the field of optical spectroscopy, line spectra can be selectively recorded in this manner. In this case, only components of the incident radiation in a spectrally small band and with a correspondingly large coherence length contribute to the signal measured.

On a use in the field of optical data transmission, carriers with defined autocorrelation properties can be selectively recorded or measured. This is in particular interesting for an application in the field of coherence length multiplexing.

The special advantage of the arrangement for both areas of application lies in the fact that the spectral resolution (spectroscopy) or bandwidth (data transmission) can be set independently of the line width to be selected (spectroscopy) or of the autocorrelation length (data transmission).

A highly extremely compact and cost-effective possibility to realize an arrangement in accordance with the invention is shown in Figure 4. A diffractive optical element (D) is used in accordance with claim 11 in a function in accordance with claim 27, in this case a diffuser with a granularity of a suitable order of magnitude. The requirement for the operation is in turn a coupling of the light field (M) in the form of only one or fewer spatial modes in accordance with claims 4 to 6. A suitable aperture diaphragm (A) as shown is advantageous. The variant shown expediently has an image-providing detector (CCD) in accordance with claim 10. Instead of the diffuser, depending on the application, diffractive elements in accordance with claim 25 can be used which can generate a highly structured interference field. A variant of the

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Talbot effect or of the Lau effect, in particular the capability of specific structures to image themselves, can also be utilized in this context. Optionally, different interference fields can be generated by a spatial displacement of the coupling or a displacement or tilting of the diffuser in accordance with claim 15.

This arrangement is expediently operated with a very high number of measurement points for the interference field in combination with the statistical methods shown.

The selectivity of the arrangements can be improved in that parts interact a plurality of times with the light fields, in particular when the arrangement permits a plurality of reflections or forms a resonator. Figure 5 shows an arrangement in accordance with the invention in accordance with claim 16 having this property.

A coupling of the light field (M) in accordance with one of the claims 4 to 6 is again required to generate recognizable interference fields. A suitable aperture diaphragm (A) as shown is advantageous. The resonator is formed in accordance with claim 17 by the beam splitter (S) and a diffractive element (G) which simultaneously serves as a beam splitter itself over different orders of diffraction. The field is coupled via the beam splitter (S) into the resonator; the resulting interference field in the direction of the detector (CCD) is uncoupled via the diffractive element (G). Further partial beams reflected a plurality of times likewise contribute to the interference.

In addition to simple gratings, on the one hand, and complex diffraction structures, on the other hand, multiplex gratings (superimposition of a plurality of spatial frequencies) or gratings sub-divided a plurality of times, for instance as illustrated in Figure 6, are also suitable as a diffractive element. In this example, the beam splitter (S) is realized as a semi-transmitting mirror, whereas the diffractive element (G) in the form shown is realized by strip-like gratings disposed next to one another with different grating constants. The part of the field reflected by the respective gratings (0th order of diffraction) exits the resonator, whereas the part of the light field

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diffracted by the gratings (requiring a suitable wavelength) initially remains in the resonator and again partially reaches the diffractive element via the beam splitter (S).

The technical design of the resonator in this process is of subordinate importance. In addition to simple resonators having only two components, all types of resonators, in particular also ring cavities, can be considered.

Very complex patterns result from the multiple reflections which are preferably treated with the help of the statistical methods named in the method claims (cross-correlation) with a very high number of measured values.

A further aspect in accordance with the invention provides for the apparatus to have means for the rotation of the interferometer or means for the changing or selection of the angle of incidence which permit an adjustment of the spatial frequency or of the spatial frequencies of the generated interference pattern.

The wavelength range which the arrangement can detect without moving parts is given by the capability of the detector to detect the corresponding spatial frequencies in the interference pattern. It can be of particular advantage for a technical realization of the arrangement to achieve the selection of a wavelength range, i.e. in this case the setting of the interferometer such that the spatial frequencies resulting for this wavelength range can be detected by the detector, by a rotation of the interferometer as a whole or by a suitable change of the angle of incidence. For this design, the interferometer itself manages without any moving elements – with the exception of the optionally required means for phase modulation – and can nevertheless be used for different wavelength ranges.

In this case, the components of the interferometer can be fixed with respect to one another, which has an advantageous effect on the stability of the adjustment. It is a

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requirement for the adaptation of the wavelength over the angle of incidence that the angle at which the partial fields are superimposed in the interferometer, shows a suitable dependence on the angle of incidence. This is e.g. the case when the partial fields are superimposed in a mirror image, i.e. the partial fields must be guided over a number of mirrors different by 1 in each case in an interferometer asymmetric in this respect.

In accordance with a further advantageous aspect of the invention, this situation can be achieved by the use of a dieder or retroreflector with symmetrical interferometers.

Figure 7 shows a particularly advantageous arrangement in accordance with claim 30. The light field is coupled (M) in accordance with one of the claims 4 to 6. The aperture diaphragm (A) bounds the solid angle to avoid scattered light.

The light field is then incident on a diffractive structure in accordance with claim 27 or 28 (diffraction grating), preferably made as a grating or as a multiplex grating. Holographically optical elements can be used very advantageously at this point. The reflected portion of the field is incident on a mirror (S2), the diffracted portion of the field is incident on another mirror (S1). Portions of the respective partial fields are reflected back from the mirrors to the diffractive element and are there superimposed to form two interference fields by respective partial reflection and diffraction. One of these interference fields reaches the detector (CCD) as described in claim 30. The patterns recorded by the detector can then be further processed numerically in the manner shown. Other parts of the fields exit the arrangement unused. The actuator (phase shifter) shown at one of the mirrors (S2) permits the recording of interference patterns at different relative phase positions of the partial fields.

The arrangement shown in Figure 8 forms a particularly advantageous combination. Beyond the element for coupling the light field (M) already shown in Figure 7, an aperture diaphragm (A), mirrors (S1, S2), a diffractive element (diffraction grating)

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and the detector (CCD), in accordance with claim 31, an imaging optical element (L) and an exit aperture (A2) can be used. The exit aperture restricts the variability of the interference patterns, which occur. For the case that the diffractive element is a diffraction grating, the exit aperture can also restrict the wavelength range of the fields, which reach the detector.

The correlation required for a measurement of a measured interferometer pattern with the interferometer pattern known for a specific spectral component or for a group of spectral components can very advantageously take place directly optically with the help of a mask and, optionally, suitable phase modulation or another form of detuning of the interferometer.

The interference patterns of a spectral fingerprint with a plurality of spectral components can in particular be already contained in a single mask.

The multiple recording of the interference pattern through the mask positioned in front of the detector at different relative phase positions of the partial beams shows a strong dependence of the respectively measured integrated total intensity of the signal on the relative phase position only for those spectral components of the incident light with whose interference patterns the mask correlates.

A direct optical correlation is much superior to numerical methods under favorable circumstances. This form of the arrangement becomes particularly interesting with the use of a variable mask, for instance of an LCD screen (spatial light modulator, SLM). A variable amplitude mask (SLM) which can show different samples for optical correlation can be realized relatively simply since the mask is no longer part of the actual interferometer.

In accordance with a further advantageous aspect of the invention, the change of the relative phase position of the interfering part fields and the change of the spatial

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frequency or spatial frequencies of the generated interference pattern takes place jointly by a movement of at least one component of the apparatus.

It is advantageous to make measurements at different relative phasings of the partial fields. If the optical path lengths of the partial fields are not equal and/or if the tilting of the optical elements results in a change of the difference of the optical path lengths of the partial fields, the relative phase position of the interference pattern also changes on the setting of the wavelength. This effect can be utilized directly for the measurement of the different phase positions. This is particularly advantageous for a technical design, since a separate mechanism for the modulation of the phase position can then be omitted.

The rotation of one of the optical elements about a support point P outside the beam path simultaneously effects a change of the optical path length and thus a modulation of the relative phase position in addition to the change in the angle and thus to the setting of the selected wavelength.

In accordance with a further advantageous aspect of the invention, the spectrally dispersive or diffractive element is a multiplex grating, a multiplex hologram, a holographically optical element or a computer-generated hologram (CGH).

When a two-dimensionally resolving detector is used, it can be particularly advantageous to use spectrally dispersive elements which do not only effect a simple deflection of the respective partial beam. The generation of complicated interference patterns appears advantageous in particular in connection with the correlation methods shown. Such complex patterns optionally show a more sharply defined correlation signal than simple stripe patterns.

When a periodic diffraction grating is used, the positions of equal optical path length and thus the maximum amplitude or modulation for the different wavelengths lie (in

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contrast to a normal Fourier transform spectrum!) at different positions of the detector. This has a favorable effect on the required dynamic range of the detector element.

For special applications, for instance in chemometrics, the demonstration of a substance by the determination of spectral "fingerprints" in specific ranges of an absorption spectrum, or the simultaneous determination of specific spectral lines, special diffraction gratings can be used – as also in the other arrangements in accordance with the invention. In addition to spatially separate or spatially superimposed multiple gratings and, optionally, an arrangement having a plurality of detectors, holographic elements can also be considered here which can e.g. diffract whole groups of different spectral lines at the same angle. This variant can be used particularly favorably when a detector is used which uses a mask for the detection of patterns (optical correlation method).



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